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EXPERIMENTS WITH MAGNETOSTATIC PUMPING OF TRANSVERSE ELECTRON BEAM WAVES

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BY

K BLØTEKJÆR
B MÅLSNES
A NORDBOTTEN

FORSVARETS FORSKNINGSINSTITUTT
Norwegian Defence Research Establishment
P O Box 25 - Kjeller
Norway

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TECHNICAL NOTE

EXPERIMENTS WITH MAGNETOSTATIC PUMPING OF TRANSVERSE ELECTRON BEAM WAVES

K Blötekjær
B Målsnes
A Nordbotten

Norwegian Defence Research Establishment, Kjeller, Norway

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EXPERIMENTS WITH MAGNETOSTATIC PUMPING OF TRANSVERSE ELECTRON BEAM WAVES

SUMMARY

The report describes an experimental tube designed to investigate magnetostatic pumping of cyclotron and synchronous waves on an electron beam. The tube consists essentially of an input coupler and an output coupler, separated by a long drift tube, which is part of the vacuum envelope. The magnetostatic structures are mounted on the drift tube, external to the vacuum system, and they are therefore readily interchangeable.

Various structures are described, the experimental program is discussed, and some results are presented. Unexpectedly high current interception foiled many of the experiments. The beam expansion and interception appeared to be much larger than predicted by theory, and the mechanism behind it is not fully understood.

1 INTRODUCTION

The current interest in transverse-wave electron beam devices originated from the successful experimental work by Adler, Hrbek and Wade, resulting in the low noise cyclotron-wave parametric amplifier (1). Initiated by the experiment, theoretical investigations of transverse electron-beam waves have been carried out, revealing a previously unexplored area in the field of interaction between electron beams and electromagnetic fields. In some respects the transverse waves are analogous to the longitudinal waves and supplementing these, but they also introduce a number of interaction mechanisms which have no equivalence in longitudinal waves. The theory of transverse interaction is far from complete, but it has been brought to a state where it predicts the fundamental properties of the various interaction schemes. However, the theoretical work has not been followed up by experiments, and possible advantages of transverse modulation as compared to longitudinal modulation are far from being utilized in practical devices.

The present report deals with an experimental investigation of some of the transverse interaction schemes. The work was intended as an experimental comparison of dc-pump structures appropriate for amplification, and evaluation of some of the more practical properties, such as maximum gain, noise performance, and effiency. The experimental plan also included testing of some fundamental phenomena predicted by theory.

An extensive investigation of these characteristics required a flexible experimental system, with interchangeable structures. It was decided to make a sealed-off tube and to have the structures external to the vacuum system. This design facilitates mechanical modifications of the structures, and assures that all comparative investigations are performed with identical electron gun and focusing system. Technologically, the design can be realized in two different ways: the vacuum envelope can be made of a dielectric, allowing all kinds of electromagnetic fields to penetrate, or it can be made of a metal, restricting the investigation to magnetostatic structures. The former technique requires some means for avoiding electrostatic charges to accumulate on the dielectric walls. This problem of course does not appear if metallic walls are used, as in the experiments reported here. Even if this allows only magnetostatic structures to be tested, a large number of experiments can be performed.

2 TUBE DESIGN

Figures 2.1 and 2.2 show a drawing and a photograph of the tube, respectively.

Basically, the tube consists of an electron gun, an input coupler for excitation of a transverse wave, a metallic drift tube with the external magnetostatic structures, an output coupler for extraction of the amplified wave, and a collector.

The simple Cuccia-coupler was chosen as the coupling element. The coupler consists of two parallel plates, and couples almost exclusively to the fast cyclotron wave (2). The parallel plates are made resonant at 600 Mc/s by means of a coil. A coaxial line is tapped to the coil, the tuning and coupling being fixed. The transmission line is matched to the couplers by means of external tuners. The coupler plates are mounted on four sapphire rods in a copper housing. The two coupler housings are connected by a copper-plated molybdenum drift tube with the couplers located perpendicular to each other. The wall of the drift tube is made thin, thus permitting the magnetostatic structures to be mounted close to the electron beam.

The gun is mounted on a socket attached to the tube by a demountable copper gasket seal. This was done in order to facilitate modifications of the gun, and to test the pump structures with different guns. In all experiments performed so far only one gun has been used. It employs a L-cathode with a diameter of 3 mm. The first anode has a 0.8 mm aperture. The gun has three anodes, and the end-plate of the input coupler housing serves as a fourth anode. This plate and the far end-plate of the output coupler housing are made of kovar, thus shielding the cathode and the collector from the magnetic field.

The tube is mounted in a solenoid producing the longitudinal magnetic field. The external steel pole-pieces are connected to the kovar end-plates of the tube. The direction of the magnetic field near the end plates can be adjusted slightly by tilting the external pole-pieces.

The primary mechanical parameters of the tube are given below.

	mm
Cathode diameter	3
Aperture, first anode	0.8
" second "	1.2
" third "	0.8
" fourth "	1.0
Spacing between cathode and first anode	0.35
Spacing between anodes	0.50
Thickness of anodes	0.25
Inner length of coupler housing	30
Inner diameter " "	35
Length of coupler plates	20
Width " " "	7
Spacing between - " -	3
Inner diameter of drift tube	2.6
Outer " " " "	4.5
Length of drift tube	59
Spacing between coupler housings	53
Aperture, second kovar disc	3

The electrical characteristics of the couplers are given below:

	Input coupler	Output coupler
Resonant frequency	607 Mc/s	608 Mc/s
R_{sh}/Q	130 Ω	125 Ω
Unloaded Q	379	400
Coupling factor β	6.66	5.95

3 STRUCTURES

3.1 Amplifying structures

The transverse waves on an electron beam can be amplified in suitable magnetostatic structures (3,4,5). The structures can be classified according to the waves which are amplified, cyclotron waves, synchronous waves, or both. The structures investigated are the following:

Structure	Periodicity	Amplified waves
Periodic quadrupole	$\lambda_c/2$	Cyclotron
Two-dimensional structure	$\lambda_c/2$	Cyclotron
Straight quadrupole	∞	Synchronous
Cylindrical structure	λ_c	Cyclotron and synchronous

Since the Cuccia coupler excites only a fast cyclotron wave, the straight quadrupole structure can not be used in connection with this coupler. However, structures exist which convert cyclotron waves to synchronous waves, and vice versa. In combination with this type of structure, the Cuccia coupler is virtually a synchronous wave coupler, and can be used for investigation of synchronous wave amplification in the straight quadrupole.

3.2 Converting structures

Two different structures for conversion between cyclotron and synchronous waves have been described. One is a periodic quadrupole of periodicity equal to the cyclotron wavelength (3,5). If the product of the field amplitude and the structure length is correct, a cyclotron wave is completely converted into a synchronous wave, and vice versa. This scheme has been shown to operate successfully with electric quadrupoles (6), and in principle a magnetic quadrupole should be equivalent (3).

The second method for converting cyclotron waves into synchronous waves makes use of a magnetic field reversal (4,7). If the longitudinal magnetic field is reversed within a small fraction of a cyclotron wavelength the conversion is complete. In practice, however, the reversal takes place over a longer region, and the conversion is not complete. Therefore, this scheme is not suited for experiments requiring pure synchronous wave excitation. On the other hand, the scheme has several advantages for practical applications, because of its simplicity and the fact that the conversion takes place over a relatively short region. The latter point is of particular importance for large-signal operation, and the scheme may find applications in high-efficiency tubes.

3.3 Structure design

The magnetostatic fields required for the interaction schemes described in Sections 3.1 and 3.2 can be produced in three fundamentally different ways, either by using separate coils with magnetic polepieces arranged in the proper pattern, or by introducing pieces of ferromagnetic material, perturbing the homogeneous magnetic field, or by using permanent magnets. Only the two former methods are used in the present experiments. The first method will be referred to as active, the second as passive.

3.3.1 Active structures

The greatest flexibility in adjusting the pump amplitude is obtained by using properly arranged coils to produce the magnetostatic fields. Sufficiently strong periodic magnetic fields can not be obtained without introducing magnetic polepieces. The presence of the polepieces will also perturb the homogeneous longitudinal field. This latter effect is utilized in the passive structures to be described in the next section, but in the present case it is an undesired effect which should be kept down to a minimum. The undesired perturbation depends mainly on the thickness of the polepieces, which should be small. Since the pump amplitude is limited by the flux through the polepieces, their minimum thickness depends on the saturation flux density of the material, which should be as high as possible.

It should be noted that the periodicity of the field due to the perturbation of the homogeneous magnetic field is half that of the active field, and therefore constitutes a second harmonic component of the actual pump field. The second harmonic would be expected to have very little effect on the beam waves. Nevertheless, the presence of the polepieces appeared to be the main reason why some of the experiments were unsuccessful.

Four active structures were built and tested. They are shown schematically in Figure 3.1. Those parts of the figures shown by solid lines represent flat steel polepieces of 0.53 mm thickness, equally spaced along the drift tube, which is shown as a black circle. The dotted lines represent polepieces placed between the solid-line set. The coils indicated in the figures produce the magnetic pump field. The current in the coils will be referred to as "pump current".

3.3.2 Passive structures

The passive structures consist of pieces of ferromagnetic material producing the pump field by perturbing the homogeneous longitudinal field. The passive structures are mechanically much simpler than the active structures and they can easily be changed or modified. The pump amplitude, the structure length, and the periodicity can be varied by changing the geometry of the structure. However, the pump amplitude can not be varied continuously or electronically, which is the major disanvantage of the passive structures. Figure 3.2 shows the basic configurations of the passive structures. All parts are made 1 mm long, and identical pieces of nonmagnetic material are used as spacers. By stacking magnetic and nonmagnetic pieces in various sequences, the periodicity and amount of perturbation can be varied in steps.

4 EXPERIMENTAL PROGRAM

4.1 Introduction

Due to unexpected difficulties some of the planned experiments could not be performed, and others were not successful. Therefore, it seems appropriate first to give a brief description of the experiments as they were planned, and to discuss the experimental results in a separate section.

4.2 Comparison of amplifying structures

The first experiments were aimed at a comparison of the pump schemes described in Section 3.1, with respect to the following properties:

a) Maximum gain
b) Noise figure
c) Efficiency

The maximum gain of transverse wave amplifiers is limited mainly by expansion of the beam in the pump field. The rate of expansion depends on the details of the electron gun, the type of pump field, and the pump amplitude. Using a simplified model, the expansion can be calculated, but many of the assumptions are rather dubious, and most experiments seem to indicate that beam expansion is more serious than expected from theory.

For each structure the experiments aimed at measuring the maximum gain for a given structure length, and in particular, determine the length which resulted in maximum gain.

A proper design of the gun is of primary importance for high gain amplifiers. However, development of a suitable gun was considered beyond the scope of the present work.

Different schemes have been proposed to reduce the noise in transverse wave amplifiers (8,9,10). They all require a special design of the gun and focusing system. The gun used in the present tube was not designed according to these principles. Still, measurement of the noise figure for the various amplifying structures was considered to be valuable. Some adjustment of the four anode voltages could be performed to optimize the noise performance.

Very little information exist on the effiency of transverse wave tubes. All calculations are based on very simplified and unrealistic assumptions. It appears that, ideally, there may be some possibility of obtaining high effiency using depressed collector potential. An experimental investigation of the effiency of the various operating conditions is therefore of great importance.

4.3 Investigations of converting structures

The structures described in Section 3.2 have not been throroughly investigated experimentally. The planned experiments included an investigation of the operation of these structures under various conditions. For the periodic quadrupole structure the experiment involved measurement of the optimum beam velocity for interaction, and the required pump amplitude for complete conversion of cyclotron waves into synchronous waves. These results can be correlated with the investigation of the same quadrupole used as an amplifying structure, at a beam velocity twice that required for conversion. Further, both types of converting structures, the quadrupole and the magnetic field reversal, should be tested in order to determine the degree of conversion, the effect on the beam focusing, and operation under large-signal conditions.

4.4 Cyclotron-synchronous wave coupling in amplifiers

In an amplifying structure of rotational symmetry the basic coupling takes place between a cyclotron wave and a synchronous wave, causing growth of both waves. In the other amplifying structures, such as the quadrupole, the cyclotron-synchronous wave coupling is much weaker, but still it is of great importance, particularly in low noise amplifiers. This coupling can be investigated by using two cascaded structures. The first structure converts the cyclotron wave originating in the Cuccia coupler into a synchronous wave. The second structure is the amplifving structure to be examined. The output Cuccia coupler extracts the cyclotron wave which originates in the amplifier. Of course, the two structures can also be applied in opposite succession, in order to investigate the synchronous wave output from an amplifier with a cyclotron wave input.

4.5 Measurement of beam noise

The amount of fast cyclotron wave noise carried by the beam can be determined by measuring the noise power extracted by a matched Cuccia coupler. If the input coupler is shorted, the output coupler can be used for the measurements. By applying a periodic quadrupole on the drift tube, and operating it as a cyclotron-synchronous wave converter, the noise on the positive energy synchronous wave can also be measured. Moreover, with a pump amplitude less than the value required for complete conversion, the output cyclotron wave amplitude is a linear combination of the input cyclotron wave and synchronous wave. Hence, the correlation between cyclotron waves and synchronous waves can be calculated from the output power. These quantities, namely the cyclotron wave noise power, the synchronous wave noise power and the correlation between the two, yield valuable information about the basic mechanism of noise generation and transformation in the gun region and the drift tube.

5 EXPERIMENTAL RESULTS

5.1 Investigation of the tube without pump field

Before starting the investigation of the various pump structures it was necessary to determine the characteristics of the Cuccia couplers, by measuring the electronic admittance of the couplers under various operating conditions and the RF-attenuation between the input and output transmission lines. The results were compared with theory, and in general the agreement was very good. However, under certain circumstances gain was observed. The investigation of this effect has been reported in another Technical Note, and only a few additional facts shall be given here (11).

It was observed that the gain increased if the end polepieces were adjusted to increase the intercepted current. This observation has been verified in another experiment, in which a small coil was applied to the drift tube, near the input coupler. The coil produced a transverse magnetic field causing a deflection of the beam. The gain always increased when the deflecting field was increased. This indicates that a helical dc-motion of the beam is significant for the gain mechanism.

It was mentioned in reference (11), that a large fraction of the beam was intercepted on the drift tube when gain was observed. More recent experiments show that gain can also be obtained with negligible current interception. This fact indicates that interception and secondary emission effects are not essential for the gain mechanism.

The theoretical part of reference (11) requires some corrections. First, the expressions for the field components, Eqs (5.1), should have opposite sign, and read

$$
\begin{aligned}
E_x &= -\frac{Kr_o}{a^2 - r_o^2}\cos\varphi - \frac{Ka^2}{(a^2 - r_o^2)^2}\,x \\
&\quad - \frac{Kr_o^2}{(a^2 - r_o^2)^2}\,(x\cos 2\varphi + y\sin 2\varphi) \\
E_y &= -\frac{Kr_o}{a^2 - r_o^2}\sin\varphi - \frac{Ka^2}{(a^2 - r_o^2)^2}\,y \\
&\quad - \frac{Kr_o^2}{(a^2 - r_o^2)^2}\,(x\sin 2\varphi - y\cos 2\varphi)
\end{aligned}
\qquad (5.1)
$$

In these equations, r_o is the radius of the spiralling motion of the dc-beam, a is the radius of the drift tube, x and y represent the transverse RF-displacement, and

$$K = I_o / 2\pi \varepsilon_o v_o \tag{5.2}$$

where I_o is the dc-current, and v_o is the axial dc-velocity. The angle ϕ is determined by the dc-rotational frequency of the beam. In reference (11) it was given as

$$\phi = \omega_c z / v_o \tag{5.3}$$

However, due to the first terms on the right-hand side of Eqs (5.1) the frequency of the stationary dc-motion is not equal to ω_c, but is rather given by

$$\omega_1 = \frac{1}{2} \left(\omega_c + \sqrt{\omega_c^2 - \frac{4eK}{m(a^2 - r_o^2)}} \right) \tag{5.4}$$

Further, in reference (11), the second terms of Eqs (5.1) were neglected, with the argument that they represent a field of rotational symmetry, independent of axial position, and therefore can not give rise to cumulative interaction. However, these field components cause a decrease of the natural frequency of the RF-motion, just as the first terms of Eqs (5.1) cause a decrease of the frequency of the dc-motion. The natural frequency of the RF-motion is given by

$$\omega_2 = \frac{1}{2} \left(\omega_c + \sqrt{\omega_c^2 - \frac{4eKa^2}{m(a^2 - r_o^2)^2}} \right) \neq \omega_1 \tag{5.5}$$

Since the two frequencies ω_1 and ω_2 are different, the synchronization condition required for quadrupole field amplification is not satisfied. It can be shown that all propagating factors are purely imaginary, i.e. , no growing waves exist. This means that the simple filamentary beam theory is not sufficient to explain the gain. There still is the possibility that space-charge forces in a finite diameter beam may cause the two frequencies ω_1 and ω_2 to coincide. A theoretical analysis of this problem appears to be very complicated.

5.2 Active structures

The experiments with the active structures were not successful. It was anticipated that the presence of the periodic polepieces should have a negligible effect on the electron beam. This appeared not to be true. Even with zero pump current the beam transmission was very low, so low that it was impossible to perform any significant experiments. Electronic gain of a few db was observed when the pump field was applied, and the voltage for which interaction occurred was in good agreement with theory. These are the only positive results obtained for the two-dimentional structure and the structure of rotational symmetry. The quadrupole structure was somewhat more successful. Figure 5.1 shows the measured electronic gain as a function of the pump current, for a structure of 2,3,4 and 5 periods length. A maximum electronic gain of 8.4 db was observed for a structure 3 periods long. The saturation was correlated with increased current interception. The voltage for which amplification occurs is given by

$$V = \frac{2m}{e} f_c^2 p^2 \tag{5.6}$$

where m and e is the mass and charge of an electron, respectively, f_c is the cyclotron frequency and p is the periodicity, which in our case was 6.15 mm.

We obtain

$$V = 160 \text{ volts} \tag{5.7}$$

The experimental value for maximum gain is $V = 165$ volts. The difference is probably due to rotational energy of the electrons.

The conversion of cyclotron waves to synchronous waves was also observed. For a beam voltage of 35 volts and a pump current of 30 mA a dip of 35 db was observed for the 3 periods structure. The fact that the dip was observed for a beam voltage of 35 volts , whereas the theoretical value is 40 volts , indicates that the interaction mechanism is not as simple as predicted by the basic theory.

It can be shown theoretically that if the structure operates as an amplifier, a gain of 8 db is obtained when applying the pump amplitude which corresponds to complete conversion of cyclotron waves to synchronous waves. This special pump amplitude is determined by using the same structure as a converting structure. According to Figure 5.1, the electronic gain at 30 mA pump current was 6 db , rather than 8 db.

The rather unsuccessful experiments with the active structures are not fully understood. The fact that the beam focusing is poor even without pump field, indicates that the presence of the thin iron polepieces has a profound effect on the motion of the electrons, although measurements show that the perturbation of the homogeneous field is very small. Although the iron was properly demagnitized, some remanence may perhaps play a rôle in the mechanism.

5.3 Passive structures

The passive structures are not so useful as the active structures for investigation of basic interaction phenomena, because the pump amplitude can not be adjusted. For practical applications, however, they may be of importance, because of their simplicity. It appeared that the passive structures did not cause so much beam expansion as the active structures.

The three different passive structures described in Section 3.3.2 have been investigated, the periodicity, number of periods, and pump amplitude being varied. Also with these structures the beam interception caused trouble, and satisfactory operation of the amplifier could be obtained only for special values of the anode potentials. The systematic investigation of the structures was therefore impeded, and we shall present here only some results which are representative for the measurements.

Due to the relatively high current interception measurement of noise figure is not meaningful. Also the current interception increased rapidly if the signal level was increased. Effiency measurements are therefore not very meaningful either.

The gain obtained with some structures are given below:

Structure		Quadrupole	Two-dimensional	Circular
Periodicity		5 mm	5 mm	4 mm
Number of periods		10	10	10
Beam voltage	Exp	120 V	125 V	19.7 V
	Theor	106 V	106 V	17 V
Beam current		445 μA	435 μA	325 μA
Net gain		16.0 db	5.2 db	13.5 db
Electronic gain	Exp	20.8 db	10.0 db	15.0 db
	Theor	21.5 db	15.5 db	15.5 db

The experimental electronic gain is calculated on the basis of the net gain and the transmission loss in the absence of pump fields. The theoretical electronic gain is calculated on the basis of the magnetic field amplitude measured by Hall-effect probes, assuming a filamentary beam along the axis of the drift tube. The gain of a finite diameter beam should be somewhat larger, because the pump amplitude increases with distance from the axis.

5.4 Magnetic field reversal and straight quadrupole

An experiment was performed in which the magnetic field was reversed at both ends of the drift tube. A synchronous wave amplifying structure was mounted on the drift tube. The structure is described in Sections 3.1 and 3.3.1. It is a straight quadrupole, the poles being made of thin plates of iron, spaced by nonmagnetic material.

Without the quadrupole structure the magnetic field reversals caused very little beam interception, and a transmission loss of 4 db was measured. However, the presence of the pole-pieces caused a prohibitive beam interception. Electronic gain of 6 db was observed when applying pump current.

6 CONCLUSION

The experimental technique described in the present work represents a flexible method for investigation of magnetostatic pump structures. However, it appeared that the magnetic structures caused unforeseen difficulties, in that the mere presence of the magnetic polepieces gave rise to beam expansion. Since this problem is unique for magnetic structures, it would be better to perform the same experiments with electrostatic structures. However, this requires a different and more complicated technology, since the drift tube wall must be made of dielectric material. A method to avoid electrostatic charging of the wall must therefore be developed.

A similar flexibility could be obtained with a demountable vacuum system. However, for comparative experiments the technique used here has the advantage that the gun and focusing system are identical throughout the experiments. In a demountable system the cathode has to be replaced after a few experiments, and extreme accuracy is required in order to assure that the alignment is the same for all experiments.

The beam expansion appears to be the major problem in dc-pumped transverse wave tubes, and there seems to be little correlation between experiments and theory so far. According to theory, beam expansion should occur only for spesific beam velocities, corresponding to synchronism between the electron motion and the periodic field. However, beam expansion is observed for almost any beam velocity. Due to beam expansion and interception, many of the planned experiments could not be performed. This applies in particular to the noise measurements. Because of the excess beam spread due to the presence of the polepieces, magnetic structures are probably not suited for study of beam expansion and other fundamental phenomena in transverse wave tubes. The use of electric structures would require a more complicated or less flexible technique. But basically all experiments described in the present report can be performed with electric instead of magnetic structures.

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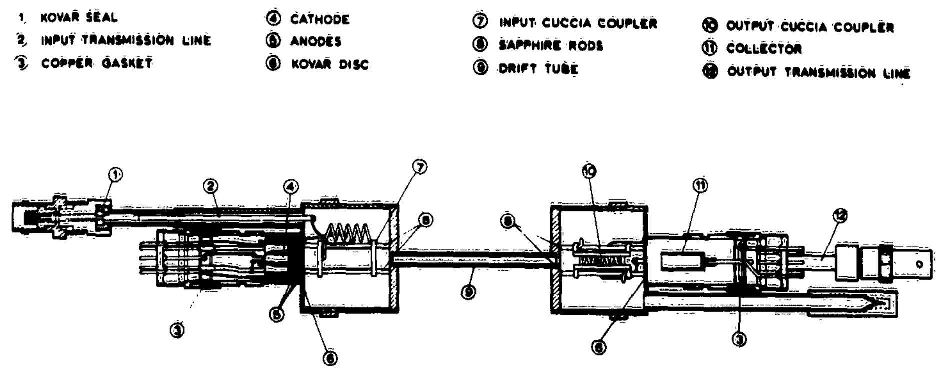

Figure 2.1 Drawing of the experimental tube

Figure 2.2 Photograph of the experimental tube

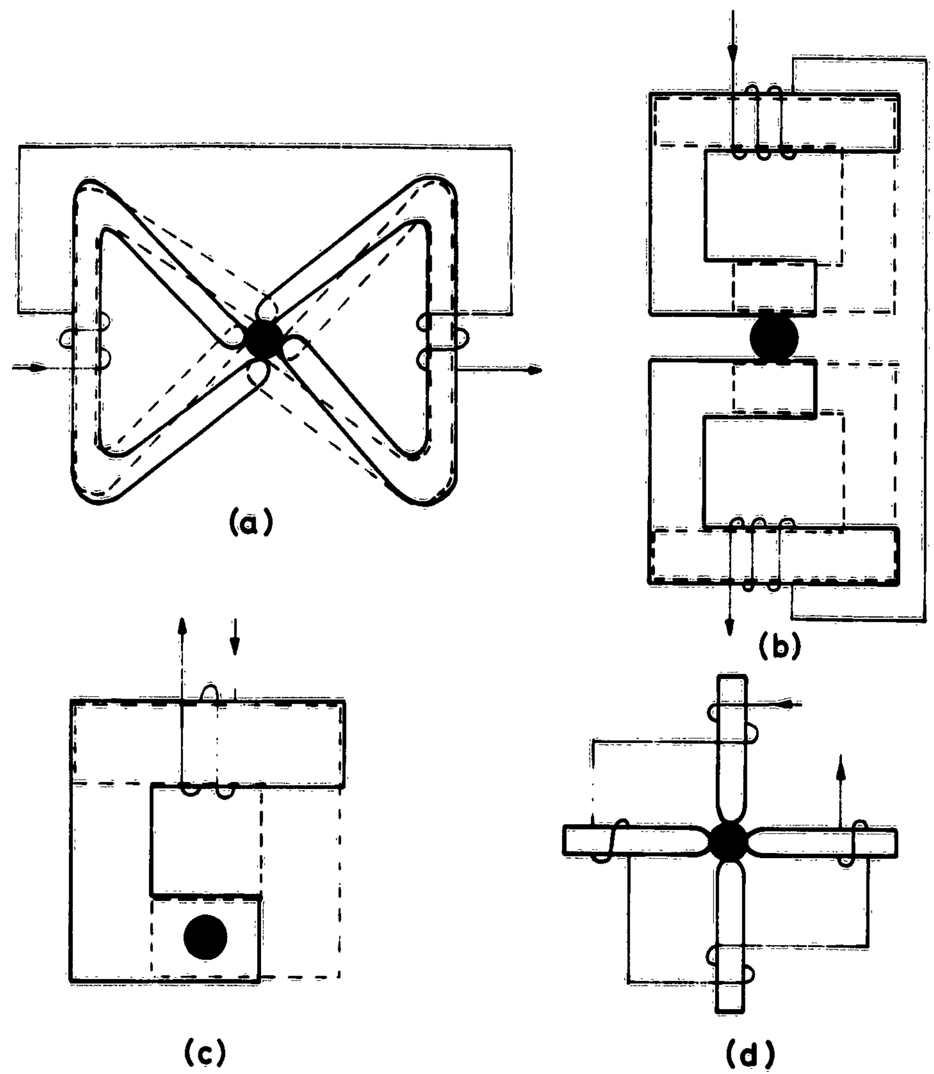

Figure 3.1 Schematic drawing of the active structures
(a) Periodic quadrupole (b) Two-dimensional structure
(c) Structure of rotational symmetry (d) Straight quadrupole

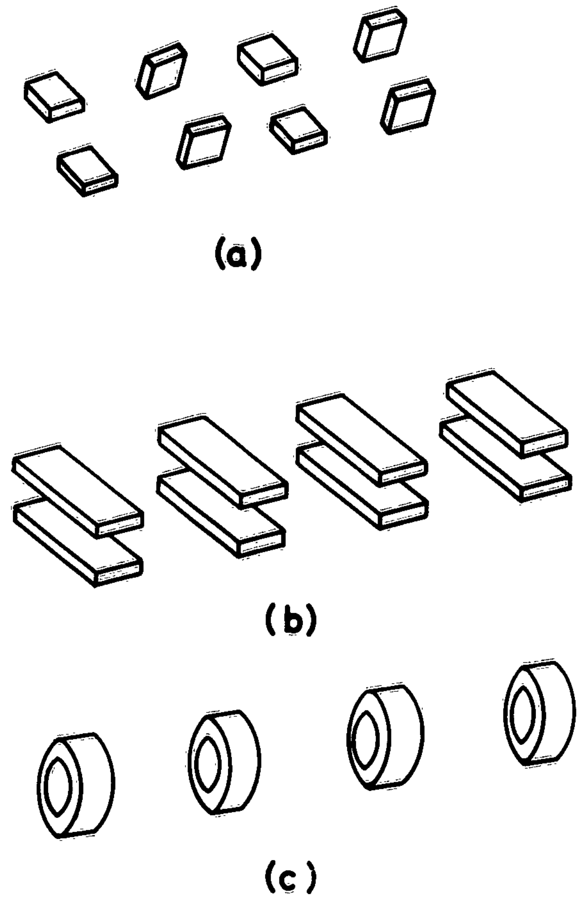

Figure 3.2 Schematic drawing of the passive structures
(a) Periodic quadrupole (b) Two-dimensional structure
(c) Structure producing a field of rotational symmetry

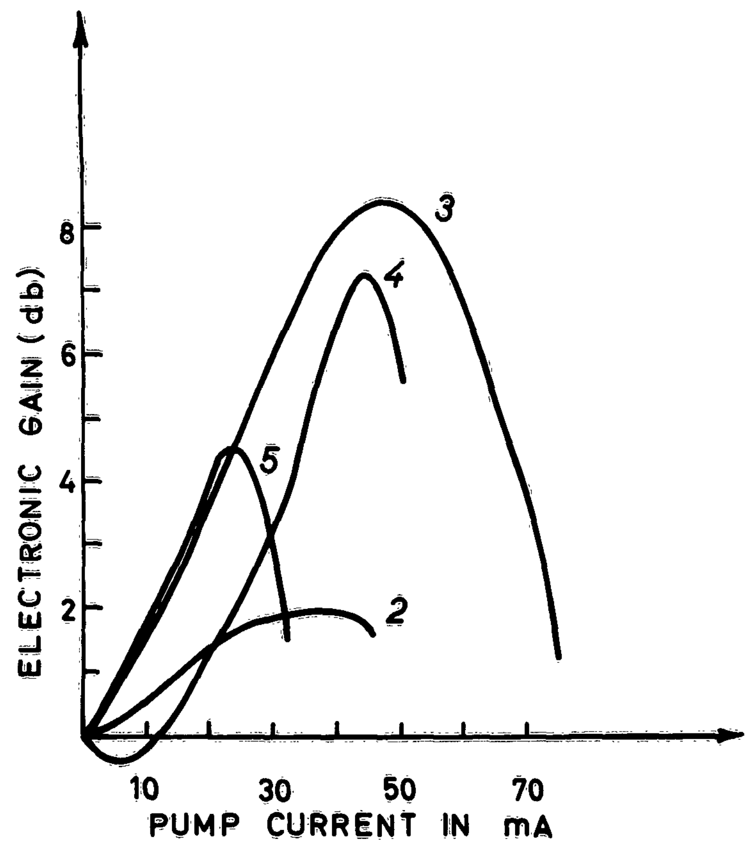

Figure 5.1 Plot showing experimental electronic gain as a function of pump amplitude for a periodic quadrupole amplifier
The curves refer to different lengths of the pump structure, two, three, four, and five periods, respectively.

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October 10. 1962

ABSTRACT: The report describes an experimental tube designed to investigate magnetostatic pumping of cyclotron and synchronous P.T.O.

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waves on an electron beam. The tube consists essentially of an input coupler and an output coupler, separated by a long drift tube, which is part of the vacuum envelope. The magnetostatic structures are mounted on the drift tube, external to the vacuum system, and they are therefore readily interchangeable.

Various structures are described, the experimental program is discussed, and some results are presented. Unexpectedly high current interception foiled many of the experiments. The beam expansion and interception appeared to be much larger than predicted by theory, and the mechanism behind it is not fully understood.

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